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Research article

The Stimuli-Actions-Effects-Responses (SAER)-framework for exploring perceived relationships between private and public climate change adaptation in agriculture

Hermine Mitter*, Martin Schönhart, Manuela Larcher, Erwin Schmid

Institute for Sustainable Economic Development, Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Vienna, Feistmantelstrasse 4, 1180 Vienna, Austria

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A B S T R A C T

Empirical findings on actors' roles and responsibilities in the climate change adaptation process are rare even though cooperation between private and public actors is perceived important to foster adaptation in agriculture. We therefore developed the framework *SAER* (*S*timuli-*A*ctions-*E*ffects-*R*esponses) to investigate perceived relationships between private and public climate change adaptation in agriculture at regional scale. In particular, we explore agricultural experts' perceptions on (i) climatic and non-climatic factors stimulating private adaptation, (ii) farm adaption actions, (iii) potential on-farm and off-farm effects from adaptation, and (iv) the relationships between private and public adaptation. The *SAER*-framework is built on a comprehensive literature review and empirical findings from semi-structured interviews with agricultural experts from two case study regions in Austria. We find that private adaptation is perceived as incremental, systemic or transformational. It is typically stimulated by a mix of bio-physical and socio-economic on-farm and off-farm factors. Stimulating factors related to climate change are perceived of highest relevance for systemic and transformational adaptation whereas already implemented adaptation is mostly perceived to be incremental. Perceived effects of private adaptation are related to the environment, weather and climate, quality and quantity of agricultural products as well as human, social and economic resources. Our results also show that public adaptation can influence factors stimulating private adaptation as well as adaptation effects through the design and development of the legal, policy and organizational environment as well as the provision of educational, informational, financial, and technical infrastructure. Hence, facilitating existing and new collaborations between private and public actors may enable farmers to adapt effectively to climate change.

1. Introduction

Adapting agricultural systems to climate change is a multi-faceted endeavor for scientists, farmers, and policy makers in order to minimize adverse and harness beneficial changes (IPCC, 2014a; Smit and Skinner, 2002). While private actors, namely farmers and agricultural producer groups, typically reduce climate-related risks for their farms and utilize business opportunities, public actors such as policy makers and government officials are committed to devote their resources to public interests (IPCC, 2014a). Still, adaptation actions by private actors – which we refer to as 'private adaptation' – may, intendedly or unintendedly, contribute to the provision of public goods or lead to negative external effects. Conversely, adaptation actions by public actors – which we refer to as 'public adaptation' – may increase or decrease private benefits (Tompkins and Eakin, 2012). A systematic coordination of privately driven bottom-up and publicly driven top-down activities is likely to increase adaptation efficiency, for instance by transferring private actors' needs and preferences into agricultural and climate policies (Bojovic et al., 2015). Individual farms and regional governance levels have been identified as most relevant for adaptation in the agricultural sector (McCarl et al., 2016; Niles et al., 2015). We therefore intend to disentangle the relationships between private and public agricultural adaptation focusing on a regional scale.

A broad variety of studies has investigated the effectiveness of

* Corresponding author.
E-mail address: hermine.mitter@boku.ac.at (H. Mitter).

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adaptation at different spatial and temporal scales and under various climate, policy and market scenarios. However, there is limited understanding if and how adaptation is taking place (Berrang-Ford et al., 2011; Ford et al., 2011) and many discussions do not distinguish the roles of private and public actors in the different stages of the adaptation process (Klein and Juhola, 2014; Smit and Skinner, 2002). Lack of clarity on private and public actors' roles, responsibilities, and benefits has been identified as a major barrier to adaptation actions and may thus contribute to the rising adaptation deficit (McCarl et al., 2016; Moser and Ekstrom, 2010; Nalau et al., 2015). Adaptation research has recently developed concepts to address the relationships between private and public adaptation. For instance, Tompkins and Eakin (2012) developed a conceptual framework on the interrelations between providers and beneficiaries of private and public adaptation and analyze how private actors may be motivated to supply public goods and services. Moser and Ekstrom (2010) provide a diagnostic framework on adaptation barriers and highlight, inter alia, the critical role of actors' perceptions, responsibilities and interactions on adaptation actions. However, there is a need to further clarify the roles and responsibilities of actors in the adaptation process (Klein and Juhola, 2014) and empirical findings on actors' roles and responsibilities are rare even though cooperation between private and public actors is perceived important to foster adaptation actions (Arbuckle et al., 2014; Hall and Wreford, 2012). Furthermore, insufficient actor-orientation of adaptation research has been identified as a reason for its limited use in adaptation decision-making (Kirchhoff et al., 2013).

We therefore aim at developing and empirically testing a novel analytical framework to explore the relationships between private and public climate change adaptation in agriculture at a regional scale. In particular, we are interested in agricultural experts' perceptions on (i) whether on-farm and off-farm climatic and non-climatic factors stimulate private adaptation, (ii) private adaption actions in and across farm sectors, (iii) potential on-farm and off-farm effects from private adaptation, and (iv) the relationships between private and public adaptation. We focus our investigation on private adaptation and how it can be supported by publicly-driven activities because agricultural experts prioritize private to public adaptation (Varela-Ortega et al., 2016). Agricultural experts are defined as intermediaries working in agricultural or environmental organizations where scientific results are typically translated into usable knowledge. Their perceptions are of major relevance because of their unique intermediary position between scientists, farmers, and policy makers and their ‘hybrid knowledge’ (Raymond et al., 2010) on the aims and priorities of the different actors. Recent studies suggest that scientific knowledge on agricultural adaptation is most likely taken up by farmers and policy makers if recommended by such information and knowledge brokers from boundary organizations (Bryan et al., 2013; Dilling and Lemos, 2011; Kirchhoff et al., 2013; McNie, 2012). Increased knowledge on agricultural experts' perceptions of factors stimulating private adaptation, adaption actions on farms, potential on-farm and off-farm effects from adaptation, and the relationships between private and public adaptation may thus facilitate private and public adaptation actions.

The article is structured as follows. In section 2, we describe the process of collecting and analyzing qualitative data to develop a novel analytical framework for exploring the relationships between private and public climate change adaptation in agriculture which is presented in section 3. In section 4, we present empirical results from Austrian agriculture using the analytical framework. In section 5, we discuss the obtained results, and in section 6 we draw conclusions and highlight further research opportunities.

2. Data and methods

2.1. Developing an analytical framework

Theories and concepts in the climate change adaptation literature have been reviewed in order to develop an analytical framework for exploring relationships between perceived private and public climate change adaptation in agriculture at regional scale. Understanding the relationships between private and public climate change adaptation is important in order to identify where public interventions are (in)appropriate to foster private adaptation in agriculture. We have identified four core components of interest, (i) factors stimulating private climate change adaptation (*S*timuli), (ii) private climate change adaptation actions (*A*ctions), (iii) effects related to private climate change adaptation (*E*ffects), and (iv) scope for public efforts to foster private climate change adaptation (*R*esponses). These core components have been combined to the *S*timuli-*A*ctions-*E*ffects-*R*esponses *(SAER)*-framework, as schematized in Fig. 1. Relationships between the core components are indicated by the dark gray arrows showing that both the adaptation process and individual core components are characterized by iterative procedures. The core and sub-components of the novel *SAER*-framework as well as their relationships are explained in section 3.

2.2. Data collection

The *SEAR*-framework was empirically refined by results from a focus group discussion and semi-structured interviews with agricultural experts in two case study regions in Austria. We selected the Mostviertel and South-East Styria as case study regions because of their heterogeneity in pedo-climatic conditions, major crops grown in the region, and the regional vulnerability of the agricultural sector to climate change. The Mostviertel is characterized by a north-south gradient with rather mild climate in the north and alpine climate in the south. Major crops grown are maize, barley and winter wheat, and dominant livestock is cattle and hog (Statistics Austria, 2016). South-East Styria belongs to the Illyrian climate zone (Prettenthaler et al., 2010). Maize, winter wheat, vegetables and fruits are most commonly grown, and hog fattening is of importance throughout the region (Statistics Austria, 2016). Results from integrated assessments until the middle of the 21st century propose that the Mostviertel is, on average, less vulnerable to climate change than South-East Styria (Kirchner et al., 2015; Mitter et al., 2015; Schönhart et al., 2014).

We have employed a mix of methods to collect qualitative data in the case study regions because of the explorative character of our research. We started with a focus group discussion in the Mostviertel in order to co-develop research questions and research design with twelve farmers and extension experts from the region. Then, we selected agricultural experts – defined as intermediaries working in agricultural or environmental organizations – combining direct and snowball sampling approaches for semi-structured interviews on their perceptions of climate change adaptation in the two case study regions. We interviewed agricultural experts because of their unique position between scientific, private, and public actors and their considerable ‘hybrid knowledge’ on the case study regions resulting from the integration of scientific, experiential, and bureaucratic knowledge (see Fig. 2 following the ‘Triple Helix Model’ by Etzkowitz and Leydesdorff (2000) and the knowledge classification schemes by Enengel et al. (2012) and Raymond et al. (2010)). Agricultural experts are thus in a crucial position to advocate private and public adaptation and their perceptions may finally facilitate developing or fine-tuning adaptation actions.

Ten agricultural experts from the Mostviertel (M1-M10) and

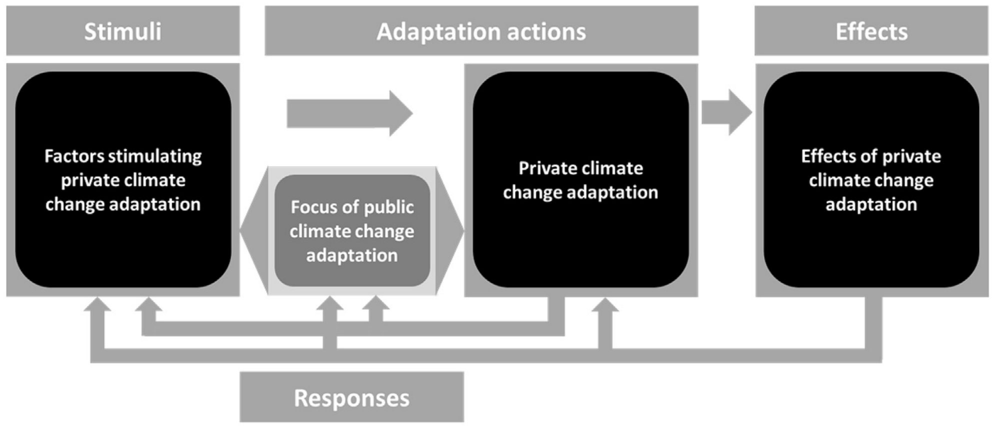

Fig. 1. Schematic representation of the core components of the *S*timuli-*A*ctions-*E*ffects-*R*esponses (*SAER*)-framework for agricultural adaptation.

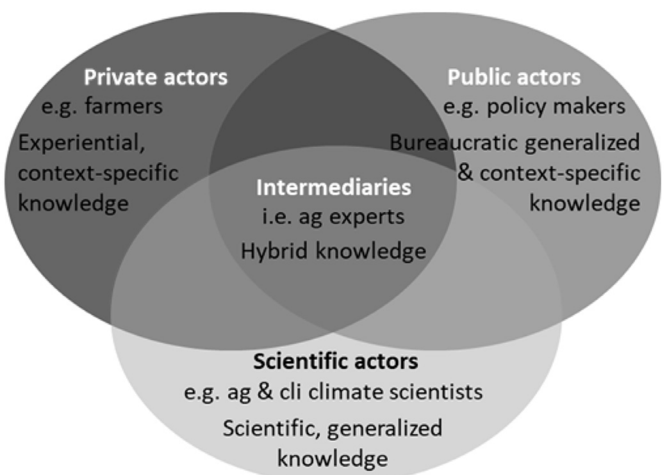

Fig. 2. Schematization of agricultural experts' intermediary position between scientific, private, and public actors. Note: ag = agricultural, cli = climate.

eleven from South-East Styria (S1-S11) participated in the semi-structured interviews. We interviewed agricultural extension specialists, staff from administration, teachers and heads of farming engineering schools, scientists and engineers of regional research organizations, representatives of agricultural cooperatives, producer groups and machinery co-operations as well as employees of regional development agencies and environmental organizations. One agricultural expert was involved in both the focus group discussion and the semi-structured interviews.

The semi-structured face-to-face-interviews have been conducted between August and October 2015 in the case study regions. The interviews lasted between 40 and 90 min each. They were digitally recorded and have been transcribed word-for-word using the easy transcript-software (in total about 255 pages, i.e. about 166,000 words). See Supplementary materials for additional information on data collection.

2.3. Data analysis

Qualitative content analysis, facilitated by Atlas.ti, has served as a means for condensing and coding collected data, interpreting the agricultural experts' statements, and evolving and specifying the sub-components of the *SAER*-framework. Deductive (top-down) and inductive (bottom-up) coding has been used (see Kuckartz, 2007) which allowed us to establish the *SAER*-framework in an iterative process, i.e. by linking theoretical knowledge from the climate change adaptation literature with findings from our empirical data analysis and vice versa. In the first step of this process, we defined theme codes deductively, i.e. based on theories and concepts presented in the literature (see section 3). These (still immature) theme codes were then assigned to relevant text passages of the transcribed interviews. The theme codes were refined based on insights from the qualitative empirical data and additional codes were created inductively, i.e. for emerging topics. Next, the refined theme codes were separated from those adding further description such as an evaluation (e.g. negative/positive) or temporal scope (e.g. past/future; see Friese, 2012). The iterative process of combining deductive and inductive coding finally resulted in the novel *SAER*-framework which is presented in more detail in the following section.

3. The novel *S*timuli-*A*ctions-*E*ffects-*R*esponses *(SAER)*-framework

3.1. Stimuli: factors stimulating private climate change adaptation

Adaptation actions have been suggested to be a reaction to a mix of climatic and non-climatic factors (Smit and Skinner, 2002) which should be further differentiated in order to relate adaptation efforts to actors' priorities and the circumstances under which they take decisions (Klein and Juhola, 2014). Following Füssel (2007) and the focus of our investigation, we categorize factors stimulating private adaptation according to their domain, i.e. bio-physical and socio-economic/socio-technical, and their level, i.e. on-farm and off-farm, which results in four basic groups (Fig. 3). Bio-physical factors refer to the natural or built environment, whereas socio-economic/socio-technical factors refer to policies, the market, the technological environment, and the characteristics of social groups and actors. Level depends on the system boundary, which is defined as the farm. Accordingly, on-farm factors relate to the characteristics of an individual farm whereas off-farm factors apply to factors relevant across farms or regions.

Based on the results from our empirical analysis, we cluster bio-physical factors into environmental factors, weather and climatic factors, and experienced impacts triggered by climate change or extreme weather events, i.e. trigger events. Several studies suggest that personal experience with climate change impacts implies action (Blennow et al., 2012; Broomell et al., 2015) and that recently experienced impacts are rated as even more important stimuli for adaptation actions (Mitter et al., n.d.). However, farmers' responses

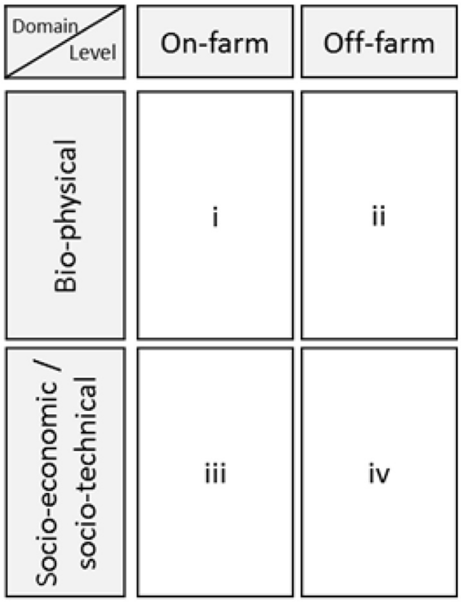

Fig. 3. Schematic representation of the categorization scheme for adaptation stimuli and effects of private climate change adaptation in agriculture.

to similar stimuli may be highly variable (Belliveau et al., 2006).

Socio-economic on-farm factors are divided into three subcategories, namely demographic, cultural, and economic factors. Demographic factors relate to 'individual objective' characteristics of the farmer (e.g. level of education) and the farm household (Ballard et al., 2013). Cultural factors refer to 'individual subjective' characteristics of the farmer (e.g. belief, attitude) and the farm household (Ballard et al., 2013). Economic factors encompass, e.g. the farm type. Socio-economic/socio-technical off-farm factors are differentiated into legal and policy, technological, cultural, and economic factors. The categories are similar to the factors of a PESTLE analysis (Political, Economic, Social, Technological, Legal and Environmental; note that the environmental dimension is covered in the bio-physical domain) which has been identified useful for analyzing factors influencing a system (Srdjevic et al., 2012; Zalengera et al., 2014).

The thematic categorization of the factors stimulating private climate change adaptation is complemented by an evaluative component. We distinguish between positive and negative stimuli, whereby positive stimuli refer to factors that farmers perceive as supportive or rewarding and thus foster or reinforce private adaptation action. Negative stimuli describe factors that farmers perceive as undesirable, impeding or hindering and are also referred to as barriers to climate change adaptation (see Antwi-Agyei et al., 2015; Arnell and Charlton, 2009; Biesbroek et al., 2013; Eisenack and Stecker, 2012; Fleming and Vanclay, 2010; Moser and Ekstrom, 2010; Shackleton et al., 2015).

3.2. Actions: private and public climate change adaptation

We define agricultural adaptation as actions taken by private or public actors in order to alleviate or avoid negative developments and take advantage of emerging opportunities due to changes in climate (see IPCC, 2014b, 2014a). We further acknowledge that changing climatic conditions may not be the sole reason for adaptation actions (see Moser and Ekstrom, 2010; Smit and Skinner, 2002). Depending on the main actor involved in the implementation process of agricultural adaptation, we differentiate between private and public adaptation.

Private climate change adaptation refers to actions taken by farmers or agricultural producer groups. Based on the adaptation type, we distinguish incremental, systemic and transformational adaptation (see Dowd et al., 2014; IPCC, 2014b, 2014a; Kates et al., 2012; Moser and Ekstrom, 2010; Park et al., 2012; Rickards and Howden, 2012; Vermeulen et al., 2013). Our system boundary is the farm level. Accordingly, incremental adaptation relates to slight and moderate changes on a farm and is often based on farmers' experience in dealing with climate variability. Systemic adaptation takes place at system level but still aims to maintain the essence of the system. Transformational adaptation changes the systems' characteristics and thus the strategic orientation of the farm. It should be noted that incremental, systemic, and transformational adaptation may overlap.

The qualitative empirical data suggest that farm sector specificities and the nature of private adaptation require some differentiation between management and investment decisions in and across farm sectors. We cluster farm sectors into plant, livestock and forest production, whereby the plant sector encompasses field crop, permanent crop and grassland production (see Iglesias et al., 2007; Nicholas and Durham, 2012; The Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2016). Even though a single farm may engage in few farm sectors, we differentiate between plant, livestock and forest production because they can be directly linked to specific private adaptation actions. Alternatively, farm sectors could be classified into cash crop, permanent crop, and forage production (including dairy and cattle farms), livestock systems of hogs, chickens, and laying hens, forest production as well as mixed farms with multiple production areas (The Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2016).

Public climate change adaptation refers to actions taken by public actors such as policy makers and government officials from different levels. We further consider private agricultural businesses and organizations as public actors if they engage in activities that are typically provided by public actors. For instance, the provision of informational infrastructure in agriculture is often a public service. Additionally, private businesses and organizations may provide new informational infrastructure, products or services serving farmers' adaptation purposes.

According to the qualitative empirical data, we categorize public adaptation into changes in the legal, policy, and organizational environment as well as the provision of public infrastructure, namely educational, informational, technical, and financial infrastructure. Public infrastructure provision is motivated by retaining agricultural land use in less favored areas and aims at *"supporting agricultural practices beneficial for the climate and the environment"* (European Parliament and European Council, 2013).

3.3. Effects: effects of private climate change adaptation

Farmers are likely to perform adaptation actions, which are most profitable under the new climate conditions. Apart from the (at least partly) intended on-farm effects, private adaptation may also exhibit off-farm effects. Following the categorization by the World Conservation Approaches and Technologies (WOCAT) program (Liniger et al., 1999; WOCAT, 2015), we differentiate between on-farm and off-farm effects of private climate change adaptation. It should be noted that on-farm effects are not necessarily related to the geographic but rather to the socio-economic entity of the farm. Furthermore, we recognize that the boundary between on-farm and off-farm effects may be blurred.

On-farm effects refer to both, deliberate and accidental effects of private adaptation that are directly related to the respective farm. Of particular interest are changes in the characteristics of the farm

system resulting from systemic or transformational adaptation. Changes in the farm system may decrease climatic risks but at the same increase a farm's exposure to other specific climatic or non-climatic factors such that perceived adaptation effects create another adaptation stimuli. An example is given by Belliveau et al. (2006) who suggest that adapting a farm to climate change by switching crops or cultivars reduces climatic stresses but at the same time may expose the farm to market risks to which it was previously less sensitive. Similarly, O'Brien and Leichenko (2000) emphasize that changes in climate and economic conditions are interconnected and results in 'double exposure' of the agricultural sector. Off-farm effects emerge from private adaptation but concern other individuals or economic sectors, adjacent or remote areas, and may alter local, regional and global ecosystems (see e.g. Fezzi et al., 2015; Kirchner et al., 2015; Tendall and Gaillard, 2015).

Similar to the thematic categorization suggested for the factors stimulating private adaptation (see Fig. 3), we distinguish bio-physical and socio-economic effects. The bio-physical domain comprises environmental, weather and climatic effects, and effects on quantity and quality of agricultural products including raw and processed materials. The socio-economic domain consists of effects on human and social resources (analogous to human and social capital, see e.g. Fey et al., 2006) and of economic effects.

The thematic categorization is complemented by an evaluation of the direction of effects, i.e. whether they are perceived positive or negative. Positive (negative) on-farm effects are associate to situations where private adaptation leads to private benefits (losses). Positive (negative) off-farm effects refer to positive (negative) externalities. The evaluation may help in identifying potential synergies and trade-offs between private and public activities. Positive on-farm effects may, for instance, contribute to climate change mitigation efforts. Negative off-farm effects may involve the risk of maladaptation (see Barnett and O'Neill, 2010; Magnan, 2014).

3.4. Responses: relationship between private and public climate change adaptation

Public adaptation can be interpreted as a stimulus for private adaptation or as a response to positive and negative effects of already implemented private and public adaptation measures. Public adaptation may thus modify adaptation stimuli, private adaptation actions, and effects of private adaptation. These feedbacks and relationships are indicated by the dark gray arrows in Fig. 4, which summarizes the novel *SAER*-framework.

Public adaptation can affect factors stimulating private climate change adaptation through the design and development of the legal, policy and organizational environment, and the provision of educational, informational, financial, and technical infrastructure. Furthermore, they should motivate synergies between positive on-farm and off-farm effects and discourage private adaptation with negative off-farm effects (see Tompkins and Eakin, 2012).

Public provision of educational, informational, technical, and financial infrastructure needs to be considered from two sides. From the viewpoint of adaptation stimuli, it is often referred to as 'institutional incentive' that influences adaptive capacity and enhances the chances of effective climate change adaptation (Gupta et al., 2010; Mandryk et al., 2015). In context of agricultural adaptation, establishing infrastructure is classified as public adaptation action (see Howden et al., 2007; Smit and Skinner, 2002) and making use of the infrastructure falls within the category of private adaptation action.

A major challenge in coordinating private and public adaptation is to deal with the complexity of interactions and relationships between private and public actors, and between adaptation stimuli, private and public adaptation actions, and effects of private adaptation. A solid basis for interactions and cooperation between private and public actors are similar spatial and temporal planning horizons, coordinated thematic priorities, and an adequate dedication of private and public resources to adaptation actions. In such cases, transaction costs arising from the coordination of multiple actors for developing, implementing and evaluating adaptation actions are rather low. By contrast, relations between private and public actors may be strained and transaction costs may be high if adaptation governance is fragmented among different levels, a strategic yet flexible adaptation plan is lacking, and actors' roles and responsibilities are not clear (Corkal et al., 2011; Hurlbert et al., 2009). Decisional conflicts may arise if public adaptation is not adjusted and timed to the needs of private actors or if public adaptation within a non-agricultural focus also affects the agricultural sector (Eisenack and Stecker, 2012). For instance, a strict biodiversity policy that constrains land use and management may limit farmers' scope for adaptation decision making. In the *SAER*-framework, we consider 'public actors' as a group of actors with a largely homogeneous interest in reducing the adaptation deficit in agriculture at regional level. However, we acknowledge that agricultural adaptation challenges public actors at local, regional, national, supranational and global levels in different ways (Adger et al., 2005).

Relationships between adaptation stimuli and private adaptation actions may be differentiated by the number of stimuli and actions involved (Fig. 5). A single stimulus causation indicates that one individual factor is perceived to drive one or several adaptation actions. A combined stimuli causation indicates that a set of factors is perceived to drive adaptation actions. With respect to the combined stimuli causation, the relevance of stimuli for adaptation actions may differ such that an actor attaches greater weight to a particular stimulus, as indicated by the different sizes of the squares in Fig. 5. Furthermore, combinations of positive and negative stimuli may occur which aggravates the development and design of public adaptation measures, as indicated by the plus and minus signs in Fig. 5. For instance, there may be several factors that are perceived as supportive for implementing a particular adaptation measure (e.g. high soil quality and freshwater availability for implementing irrigation) whereas others may impede or even limit private adaptation (e.g. low capital resources). It could also happen that a factor perceived as supportive for a particular adaptation measure is perceived limiting for implementing another adaptation measure.

Relationships between adaptation actions and effects can be categorized similar to the relationships between adaptation stimuli and actions, i.e. single and combined effects (Fig. 5). However, in most cases we would expect that adaptation measures lead to combined effects. The evaluation of effects is an important link to public adaptation, which should − in general − support socially beneficial effects and reduce welfare decreasing effects to a minimum. Most critical are adaptation measures that lead to effects beneficial for private actors but reduce total social welfare.

4. Applying the *SAER*-framework for exploring climate change adaptation in Austrian agriculture

The *SAER*-framework has been tested for agricultural adaptation in Austria by applying it to the empirical data from the two case study regions Mostviertel and South-East Styria. The results are summarized in the following sub-sections.

4.1. Stimuli: perceived factors stimulating private climate change adaptation

The agricultural experts perceive that private adaptation is

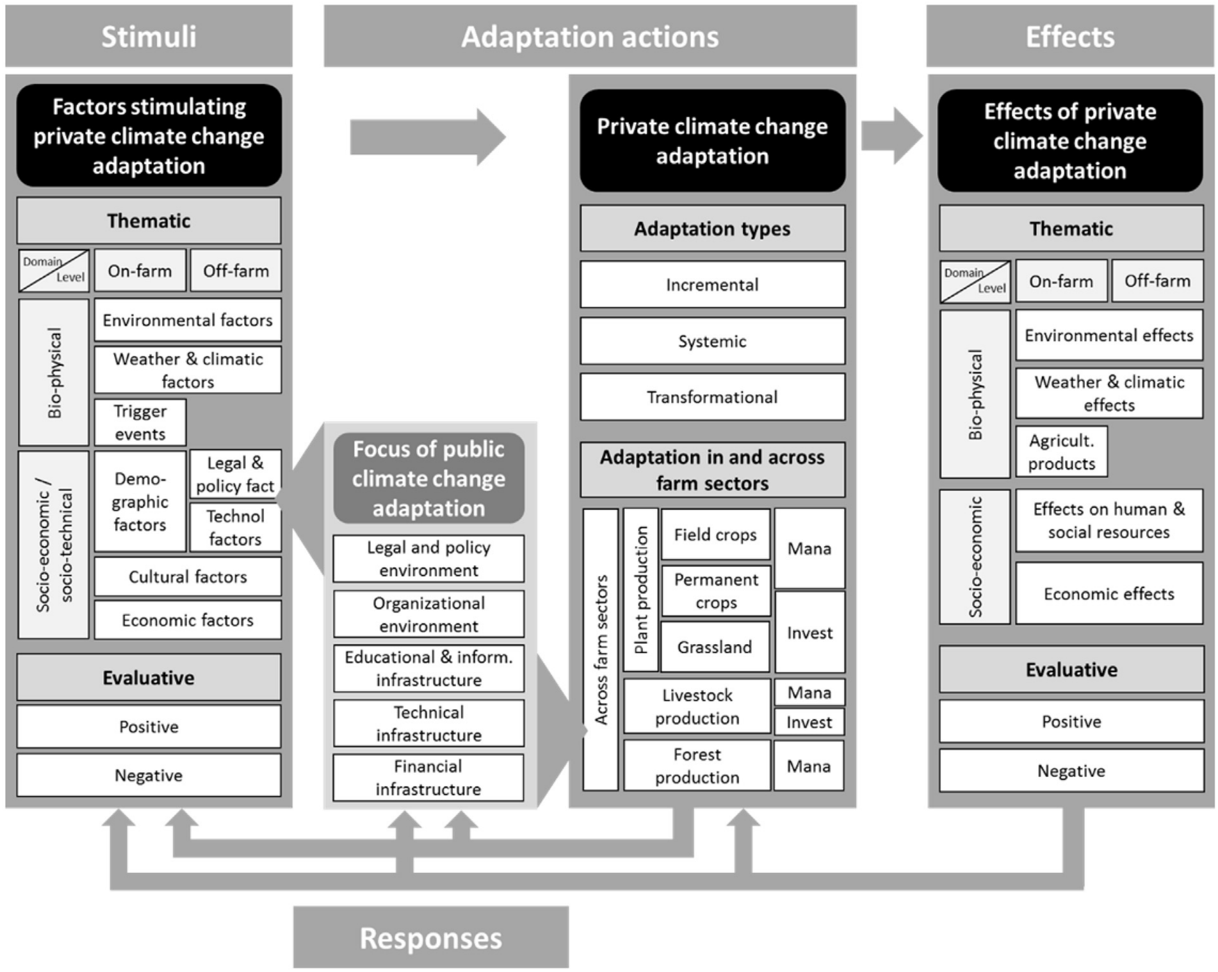

Fig. 4. Schematic representation of the novel *S*timuli-*A*ctions-*E*ffects-*R*esponses (*SAER*)-framework for agricultural adaptation. Note: Technol. = technological, inform. = informational, Mana = Management, Invest = Investment, Agricult. = Agricultural.

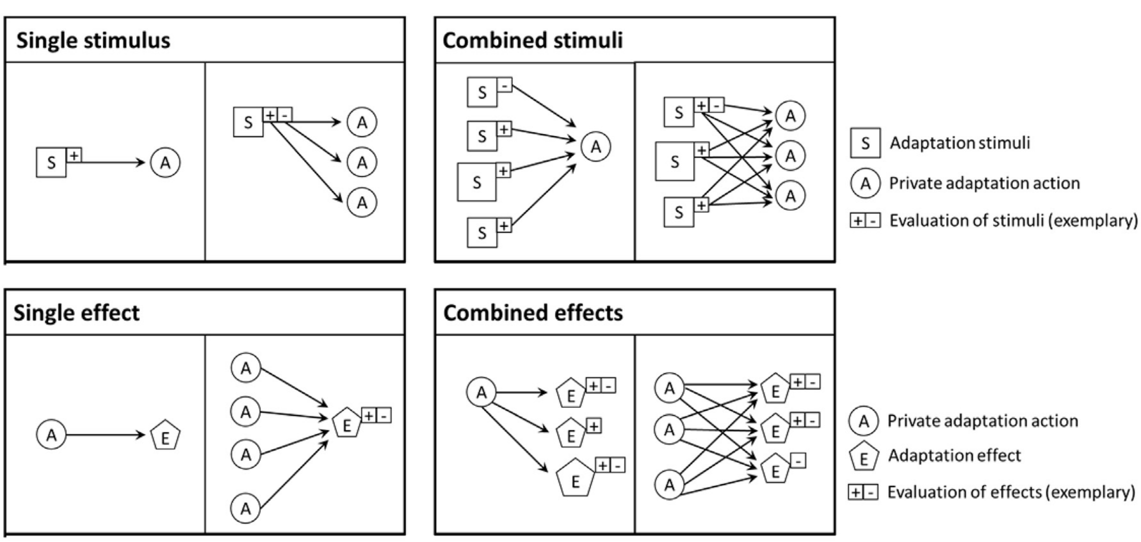

Fig. 5. Schematic representation of potential relationships between adaptation stimuli, private adaptation actions, and adaptation effects.

mostly a response to combined stimuli, as illustrated in Fig. 5. They mention a broad variety of factors, which we present following the categories of the *SAER*-framework, i.e. bio-physical and socio-economic on-farm and off-farm stimuli (Table 1).

Table 1
Factors stimulating private climate change adaptation perceived by the agricultural experts in the case study regions.

Domain	Level	
	On-farm	Off-farm
Bio-physical	**Environmental factors**	
	Soil quality	Biodiversity
	Topography	Regional land cover and land use
	Water balance	Regional water balance
	Farmland patterns	Landscape patterns
	Weather and climatic factors	
	Microclimate	Regional and global climate change
	Trigger events	
	Experienced and expected climate change impacts	
Socio-economic/socio-technical	**Demographic factors**	**Legal and policy factors**
	Age	Regulations
	Education	Agricultural policies
	Family structure, farm succession	Public payments
		Technological factors
		Agro-technological change
	Cultural factors	
	Individual attitudes, values, beliefs	Public attitudes, values and beliefs
	Farm tradition	
	Economic factors	
	Factor endowment	Output prices
	Farm type	Variable costs
		Investment costs
		Regional and national supply and demand

4.1.1. Perceived bio-physical on-farm and off-farm factors

Perceived bio-physical on-farm factors are directly or indirectly related to climate change and comprise the availability and quality of abiotic resources at farm level, farmland patterns, local weather and climate conditions, and climate-related trigger events. Abiotic factors such as soil type and topographic conditions are relatively stable over time – even under changing climatic conditions. They are perceived as preconditions for most private adaptation actions because they are rather difficult to adjust by farmers. Soil water availability highly depends on soil type and precipitation characteristics and is perceived as an important driver for yield potentials and thus adaptive management decisions in plant production. Farmland patterns refer to the spatial distribution of continuous surface patterns, point patterns, and linear networks and characterize field sizes and the distribution of landscape elements. Farmland patterns in combination with soil type and topography are perceived to stimulate investment decisions in machinery, e.g. in reduced tillage equipment.

The local weather and climate conditions may differ from the meso- and macroclimate and are perceived as a chance for farmers that global climate change is less devastating. Stabilizing the microclimate is thus perceived as adaptation stimulus. Trigger events, i.e. experienced and expected negative impacts of changes in regional climate conditions and extreme weather events, are perceived as another important adaptation stimuli and is expected to push the implementation of private adaptation:

> "*I think the most important stimulating factor is own experience. They say: 'There is no choice and we have to adapt. We can't operate in the way we were used to because we have experienced more frequent dry periods at a time when we don't need it.'" (S9)*

Perceived bio-physical off-farm factors are also directly or indirectly related to climate change and refer to the availability and quality of regional biotic and abiotic resources (i.e. changes in development cycles of pests and weeds, land use and landscape patterns, and the regional water balance), and to the changes in regional and global climate conditions.

Changes in pest and weed pressure are sometimes, but not always, seen in the context of changing climatic conditions:

> *"We have to deal with pests that we did not face in such an intensity in earlier times. For instance, pest control for potato beetles took place once a year in earlier times. Nowadays, the problem occurs very early and pest control is carried out two to three times a year. It may be partly because fungicides with adverse side effects on insects were applied in earlier times. […] But I think it is also because of higher temperature. In earlier times one generation matured per year whereas nowadays two to three generations mature per year." (M5)*

Regional land use and landscape patterns are perceived to affect biodiversity and soil erosion and thus the attractiveness of the region, e.g. for tourism. Furthermore, the regional availability of feed is perceived as stimuli for the intensity of livestock production. The regional water balance is highly sensitive to rainfall, evapotranspiration, runoff, and irrigation water demand. The availability of surface or groundwater is perceived of major importance for investments in irrigation equipment and water reservoirs. Some agricultural experts perceive changes in meso- and macroclimatic conditions important for the progress in private adaptation. Others are more skeptical and scrutinize if climate change matters a lot in decision-making or even think that some farmers do not believe in climate change.

4.1.2. Perceived socio-economic and socio-technical on-farm and off-farm factors

Socio-economic on-farm factors are perceived as non-climatic stimuli and can be attributed to demographic, cultural and economic factors. Adaptation actions are perceived to be stimulated by age and education of the principal farm operator as well as by the family structure (demographic factors). Furthermore, farmers' personality, personal objectives, attitudes, values and beliefs as well as the farm tradition are rated as important cultural factors. Cultural factors like farm traditions and farmers' habits are deemed to delay or hinder innovation. For instance, retaining crop rotations perceived as 'traditional' in the case study regions may hamper the introduction of innovative crops or cultivars. Perceived farm-

related economic factors are farm type and factor endowments, i.e. land, labor and capital. Farm type and available workforce are perceived to impede or even limit private adaptation. For instance, if a livestock farm depends on on-farm forage, this will drastically reduce a farmer's flexibility in crop choice and thus adaptation.

Socio-economic/socio-technical off-farm factors are perceived as strong non-climatic stimuli for private adaptation actions. They comprise legal guidelines and regulations at European, national and regional level, agricultural policies and public payments, the market situation and its development, agro-technological progress, and public attitudes, values and beliefs. Legal guidelines and agricultural policies may accelerate adaptive management and investment decisions:

> *"Now, we grow more sorghum because we have a legal crop rotation restriction. Currently, we are allowed to cultivate maize three times within four years." (S11)*

Similarly, policy incentives for selected managements, investments or target groups are perceived to spur private adaptation. However, inflexible, insufficient or outdated legal regulations as well as administrative burden in the context of agricultural policies are perceived to slow down private adaptation. The status and expected development of regional and global supply and demand is perceived to support or impede private adaptation actions. For instance, high agricultural output prices and high (regional) demand for specific outputs, e.g. 'new crops' or 'organic products', are perceived to encourage farmers to adapt management practices or invest in new technologies. By contrast, low levels and high volatilities of agricultural output prices as well as high investment costs for adaptation are perceived to narrow farmers' flexibility and alternatives for adaptation actions. The agricultural experts agreed that socio-economic interests are more relevant for adaptation decisions than climate-related factors:

> *"The rationale is not: climate changes. The farmer's rationale is: how can I maintain the income." (M1)*

4.2. Actions: perceived private climate change adaptation

The agricultural experts reported on the bandwidth of private adaptation in the case study regions, which we present by adaptation type and farm sectors (Table 2). Incremental adaptation is perceived in all farm sectors that are relevant in the case study regions, i.e. plant, livestock and forest production. Financial management such as purchasing an insurance product and delaying investments is perceived relevant across farm sectors. Perceived incremental adaptation is largely based on farmers' knowledge and experience and has a short-term, mostly responsive focus on keeping the current system in operation. Farmers' management decisions are perceived to be taken on a daily, weekly or seasonal basis and often follow adverse impacts or trigger events. Changing climatic conditions are articulated as 'unconscious' drivers for incremental adaptation by the agricultural experts:

> *"I think that changes in regional climate conditions play a more important role than farmers are aware of. I think they take decisions and the driver for their decisions is climate change but they are not aware of it. For instance, I am sowing two weeks earlier. […] He says, the temperature is appropriate, I am sowing now. But this is a continuous development and he is probably not aware that sowing is earlier every year – or one week earlier every ten years." (M8)*

One incremental adaptation measure, which is perceived to be taken because of changes in regional climate conditions, i.e. 'intentionally', is the purchase of insurance products against extreme events such as droughts or storms. However, insurances are perceived to impede systemic or transformational change, also because of publicly supported insurance premiums. Incremental adaptation is perceived to be mostly implemented by single farmers, i.e. without cooperation between neighbors or peers. One exception is cooperation between farmers for applying new machinery. Farmers are perceived to make use of the opportunity to test machinery provided by machinery co-operations before taking investments.

According to the agricultural experts, systemic adaptation is also perceived in plant, livestock and forestry production. It aims at keeping the current farm type. For instance, the relative shares of cropland and grassland are limited by the production orientation of the farm. Systemic adaptation typically has a long 'decision lifetime' (Stafford Smith et al., 2011), i.e. both the lead time (the time from first deliberation to adaptation action) and the consequence time (the time over which the effects of adaptation are realized) may be several years or even decades. It encompasses management and investment-related activities and may partly overlap with incremental and transformational adaptation.

Perceived transformational adaptation is mostly independent from the respective farm sector. It has a long-term focus, similar to systemic adaptation, and is typically related with higher costs, risks and potential benefits, compared to incremental adaptation. Long decision lifetimes and high costs, i.e. economic factors, are perceived as important reasons for farmers to proactively ask for information in the decision process by the agricultural experts. Furthermore, transformational adaptation may need the interaction between farmers, for instance, for regionally coordinated water management. The agricultural experts perceive changes in regional climate and economic conditions as a challenge for both, systemic and transformational adaptation. In particular, climate and economic changes are addressed as stimulating factors in the context of investment decisions (e.g. constructing new stables, establishing irrigation facilities) and land cover change, and play a role when farmers decide on the strategic orientation of their farm.

Adaptation is perceived to gain in importance in the future. Agricultural experts underline the relevance of implementing new technologies (e.g. fertigation, precision farming), changes in land use (e.g. changes in cultivars and crops) and land cover (e.g. expansion of wine growing areas), and more sophisticated financial and risk management strategies (e.g. futures and options). Irrigation is already applied for special crops (e.g. maize for seed production, wine) in both case study regions. However, the interviewed agricultural experts do not agree on the future relevance of irrigation for main crops. Opponents of irrigation doubt its sustainability because of limited water availability in the case study regions (i.e. environmental limitation) or argue that irrigation is too expensive under current market conditions (i.e. economic limitation). Proponents point out that irrigation for special and main crops is likely to be profitable if regional climate conditions continue to change (i.e. combination of climatic and economic factors). They suggest to engage in regional water management and ask for rainwater harvesting during the more humid winter season in order to allow for irrigation on cropland during the vegetation period, regardless of the cultivated crop.

4.3. Effects: perceived effects of private climate change adaptation

Agricultural experts report on combined positive and negative on-farm and off-farm effects of private climate change adaptation

Table 2
Private climate change adaptation perceived by the agricultural experts in the case study regions.

Adaptation type	Perceived private climate change adaptation
Incremental	Changes in planting and harvesting dates
	Changes in tillage, fertilizer, pesticide and irrigation management
	Changes in crop varieties and grassland seeds
	Using hail protection nets
	Applying new machinery
	Changes in stocking density in livestock production
	Adjusting feeding ratios
	Investments in insulation, ventilation and cooling of stables
	Reducing tree row densities
	Improving insect control strategies
	Purchasing an insurance product
	Delaying investments
Systemic	Changes in land cover (e.g. extending cropland over grassland)
	Changes in farm size (e.g. leasing farmland from or to neighbors)
	Converting between conventional and organic farming
	Converting between full-time and part-time farming
	Investing in new technologies
	Investing in new buildings
Transformational	Change in farm type
	Diversification of farm income (e.g. green care, agro-tourism, direct marketing)
	Farm withdrawal
	Regional water management

as outlined in Fig. 5. They are presented following the categories of the *SAER*-framework, i.e. bio-physical and socio-economic on-farm and off-farm effects.

4.3.1. *Perceived bio-physical on-farm and off-farm effects*

Perceived environmental effects of private adaptation comprise effects on soil properties, surface water and groundwater, landscape patterns and biodiversity. Perceived effects on soil include changes in soil stability and erosion, humus formation, soil water holding capacity, and soil carbon sequestration. Positive on-farm and off-farm effects are achieved with erosion control measures including conservation tillage and more diversity in crop choices, i.e. incremental adaptation:

> *"Erosion control has a positive effect on the neighbors, on the people living downstream. If water flows to their land are reduced or avoided or if mud is reduced." (M7)*

Negative effects on sediment loss are perceived if fields are enlarged by land consolidation or if cropland is expanded to steep areas or areas with currently high precipitation sums (i.e. incremental and systemic adaptation). Soil humus and soil water holding capacity are strongly interrelated such that an increase in soil humus results in an increase in stored soil water. On the one hand, the agricultural experts acknowledge the positive effect of low input farming, reduced tillage, and cultivating cover crops (i.e. incremental adaptation) on humus formation. The positive effects include a reduced risk of flooding, likely reduced nitrogen inputs, higher carbon storage capacities, and improved soil biology. On the other hand, intensive farming in terms of tillage, fertilizer and pest management (i.e. incremental adaptation) is criticized for its adverse effects on humus.

Perceived effects on water are changes in runoff and thus erosion, nutrient emissions in surface and groundwater as well as changes in the regional water balance. Surface and ground water contamination may result from insufficient adaptation or poor management decisions (i.e. incremental adaptation). Positive off-farm effects on the regional water balance are attributed to reduced tillage and cultivation of cover crops (i.e. incremental adaptation). Regional water management is perceived positive, e.g. to decrease the severity of floods. Competition between water consumers including agriculture and households is generally not perceived as a problem because extraction of irrigation water is strictly regulated.

Landscape patterns and biodiversity are perceived to be affected by incremental, systemic and transformational adaptation, especially by construction projects such as water retention basins and hail nets, changes in land cover and use including afforestation, reduction in monocultures and diversification in crop choices, ground cover in winter as well as intensification or extensification of management practices. Positive as well as negative developments are perceived. However, the agricultural experts pointed out that information, communication, and consultation ahead of implementation are critical in order to reduce opposition against new projects affecting landscape patterns and biodiversity.

Weather and climatic effects refer to the microclimate and to climate change mitigation. Positive effects on the microclimate may be achieved by maintaining or establishing landscape elements as well as by increasing soil water holding capacity (i.e. incremental adaptation). Both farmers and society may benefit from changes in microclimate (i.e. on-farm and off-farm):

> *"I am glad about every farmer who works in smaller structures and keeps his forest edge and his hedges and his trees because everybody benefits, […], even climate, microclimate. […] If a farmer manages to influence the microclimate, this is a big advantage because he is less dependent." (M6)*

Climate change mitigation was not explicitly addressed by the interviewer, but the agricultural experts referred to it in the context of humus formation and soil carbon sequestration, animal husbandry, and extensification (i.e. incremental and systemic adaptation). Smaller structures in combination with regional markets as well as low input farming are perceived beneficial in terms of climate protection because of reduced traffic and farm inputs.

Quantity and quality of agricultural products (e.g. level of crop yields, wine quality) are perceived to be influenced by incremental and systemic adaptation. In particular, changes in management practices such as timing of cultivation, crop and cultivar choice, irrigation and pesticide management as well as investment decisions are taken in order to generate positive on-farm effects. However, adverse effects may occur, depending on the weather

conditions. For instance, earlier sowing dates are perceived beneficial for crop yield levels because of higher soil water contents and reduced risk of pest damage but may result in late frost damages.

4.3.2. Perceived socio-economic on-farm and off-farm effects

Perceived socio-economic effects encompass effects on human and social resources as well as economic effects on farm income and other economic sectors. Human resources are perceived to be affected by systemic and transformational adaptation through the gain or loss in local knowledge. Organic farming is seen as a nucleus of growth in local knowledge:

> *"I think that knowledge on humus formation increases slowly. Certainly because of organic farming, it diffuses a bit." (M3)*

Additionally, developing new or rediscovering 'old' branches of production increases local knowledge. On the contrary, farm withdrawal or changing farm types contribute to the loss of local knowledge.

Social resources are perceived to gain in importance in the future because collaborative efforts of farmers are needed for erosion and pest control, water and manure management, long-term investment projects and development of markets for 'new' agricultural commodities. Collaborative activities are perceived to generate on-farm and off-farm benefits. However, farmers' actual willingness to engage in collaborations and co-operations is perceived to be rather low despite the guidance by regional agricultural and environmental organizations.

Farm income is directly affected by management and investment decisions (incremental, systemic and transformational adaptation). Changes in variable costs have been attributed to altering costs for fertilizers, tillage operations, pesticides, power, fuel, insurance, labor, and consulting. In several cases, variable costs are directly related to regional climate conditions and increase or decrease with incremental adaptation. One example is reduced costs for drying maize because of higher temperatures and later harvesting dates:

> *"With respect to maize, we can harvest it relatively late which decreases drying costs." (S2)*

Higher variable costs are perceived to be accepted if adaptation leads to positive long-term effects such as with green manuring. Additional transportation costs may occur due to changes in land use and long distances to a processing facility. Diversification of farm income (e.g. agro-tourism, green care, direct marketing) is perceived as highly labor intensive and thus increases costs.

Investments in buildings, machinery or technology because of systemic or transformational adaptation have been mentioned to co-determine fixed costs. The efficiency of investments in e.g. stables, water retention basins and irrigation equipment is perceived to depend on current and future climate, market and legal conditions, natural resource endowment, and farm characteristics such as farm size and farm type. Machinery co-operations have been promoted in the agricultural sector because of their potential to reduce or avoid misinvestments on farms. These advantages are acknowledged by the agricultural experts who evaluate the efforts and the widespread network of machinery co-operations positively.

4.4. Responses: perceived relationship between private and public climate change adaptation

The agricultural experts consider three aspects important for responding to the needs of private actors through public adaptation efforts. First, they ask for consistent and transparent legal and policy environments. Second, they suggest to develop the internal structure of and the network between the agricultural and environmental organizations they are working with. Third, they identify the great potential of agricultural and environmental organizations in providing educational, informational, technical, and financial infrastructure.

The agricultural experts suggest to re-design and develop the legal and policy environments such that organizational and institutional barriers for private adaptation are reduced. Legal certainty is considered a prerequisite for long-term adaptation investments. Legal guidelines and regulations are asked to limit negative off-farm effects and support innovative adaptation. Furthermore, the agricultural experts highlight that contradictory regulations as well as complicated administrative processes should be avoided in order to reduce transaction costs.

Perceived potential for developing a supportive organizational environment comprises of intra- and inter-organizational initiatives. According to the agricultural experts, intra-organizational initiatives could include a commitment to educational programs for employees and cross-departmental cooperation in order to capture the multiple facets of climate change adaptation. Allocating time and resources for inter-organizational collaborations is perceived to help to define responsibilities for coordinated adaptation actions, develop complementary skill sets, and may thus ensure long-term organizational engagement in agricultural adaptation.

Infrastructure provision is perceived a key task within public adaptation. All agricultural and environmental organizations represented by the agricultural experts already engage in infrastructure provision, i.e. educational, informational, technical, and financial infrastructure (Table 3). Based on their experience, agricultural experts provide several suggestions for infrastructure design. Educational and informational infrastructure are asked to be adapted to the agricultural system in the respective region and should deal with both, direct and indirect climate change impacts. They suggest to address direct impacts during and immediately after the occurrence of an extreme event. Such 'windows of opportunity' could be used to stimulate private adaptation – even if investments have to be postponed because financial resources may be limited in particularly bad years. Including indirect impacts in a regular information strategy is perceived key because farmers tend to assess indirect effects (via the market) stronger than direct climate-induced impacts. With respect to technical infrastructure, agricultural and environmental organizations may facilitate farmers' access to results from breeding activities, feed laboratories, and field trials and may support planning and construction of water reservoirs and flood protection measures. Furthermore, weather stations and agricultural machinery may be provided for lease.

With respect to financial infrastructure, publicly subsidized crop insurance products (co-financed by the national and provincial governments) are perceived controversially. The opponents think that it may hamper systemic and transformational adaptation and opt for withdrawing public subsidies:

> *"I have been trying to encourage farmers to deal with water management for quite some time. But it hasn't worked out yet. They do not really think about it. [...] Economically, it is overlaid by the hail and drought insurance. I think this is a wrong approach to overlay these things. The effects are compensated financially, though it could be corrected in nature." (S6)*

The proponents argue for improving and expanding the crop insurance system. They advocate for index-based insurance such

Table 3
Educational and informational, technical and financial infrastructure provided by the agricultural and environmental organizations in the case study regions according to agricultural experts' perceptions.

Agricultural and environmental organization	Educational and informational infrastructure	Technical infrastructure	Financial infrastructure
Regional research institute	✓	–	–
Administration	✓	✓	✓
Extension service	✓	✓	–
Farming engineering school	✓	–	–
Farm machinery co-operation	✓	✓	–
Regional development agency, environmental organization	✓	–	✓
Agricultural cooperative, producer group	✓	✓	✓

Legend:
✓ … mentioned in the interview.
– … not mentioned in the interview.

that climate-related parameters trigger insurance payments. Payments from the national disaster fund are considered important in years of heavy losses. However, the agricultural experts discern that transfers from the disaster fund are likely to impede farmers' private adaptation. Farmers tend to count on the money from the disaster fund and are thus not always prepared for extreme weather events. A transparent and easily comprehensible regulation on when agricultural producers can expect transfers from the disaster fund could help to sharpen farmers' sense of security and may foster alternative private adaptation.

5. Discussion

5.1. Stimuli: factors stimulating private climate change adaptation

The results of the semi-structured interviews with agricultural experts confirm or extend some findings of previous studies. Our empirical results support theoretical and conceptual approaches suggesting that private adaptation is stimulated by a combination of climatic and non-climatic factors (Smit and Skinner, 2002) which is also reflected in the *SAER*-framework. The presented bandwidth of stimulating factors (i.e. environmental, weather and climatic factors, bio-physical trigger events as well as demographic, economic, cultural, legal and policy, and technological factors) summarizes the perception of all interviewed agricultural experts though most of them do not perceive the full spectrum. The identified adaptation stimuli are also in-line with other empirical studies. For instance, Brown et al. (2016) show that Australian farmers perceive economic factors as most constraining and bio-physical factors as most enabling for climate change adaptation. Knox et al. (2010) identify climatic and non-climatic factors (i.e. economic, environmental and technological factors) as important motivators for agricultural adaptation. Li et al. (2017) find that economic and cultural factors, trigger events as well as access to information stimulate private adaptation. Similarly, Deressa et al. (2009) emphasize that – apart from climatic factors – demographic factors as well as access to information, social capital and financial infrastructure determine private adaptation. In the context of the ‘finite pool of worry effect’ which suggests that growing concern e.g. about economic conditions may reduce worry about climate change (Weber, 2010, 2006), it seems rewarding to distinguish between climatic and non-climatic adaptation stimuli and to address those stimuli with public adaptation actions which are related to farmers' major concerns.

Our results also suggest that both, farm-specific (on-farm) and regional (off-farm) factors affect adaptation actions. These findings confirm results from previous studies indicating that farmers base their adaption decisions on the technological and structural potential of their farm (Nguyen et al., 2016; Reidsma et al., 2010; Varela-Ortega et al., 2016) and the region where their farm is located (Lyle, 2015; Niles et al., 2015). Publicly provided infrastructure should thus be tailored to farmers' needs in regional contexts.

5.2. Actions: private climate change adaptation

Qualitative and quantitative studies have concluded that climate change may be less important for private adaptation than socio-economic factors including, for example, changes in policy or market conditions (e.g. Boissière et al., 2013; Finger et al., 2011; Lehmann et al., 2013). Our analysis supports these findings, i.e. the agricultural experts agree that socio-economic factors may be more relevant for private adaptation than climate change-related factors. In addition, the agricultural experts mostly perceive incremental private adaptation, which is based on farmers' knowledge and experience and often takes place even though farmers are not fully aware of climate change. By contrast and similar to the findings by Park et al. (2012), climatic factors are perceived particularly important for systemic and transformational adaptation. Combined with the fact that farmers actively seek for information when taking systemic or transformational decisions, this may indicate that farmers' current knowledge and experience may not be sufficient for successfully implementing systemic and transformational adaptation, regardless of the farm sector they are working in. Public adaptation should therefore address potential constraints of local knowledge in order to overcome such limitations.

Furthermore, private adaptation is rarely considered an opportunity for farmers, neither by the agricultural experts nor in the national and regional adaptation strategies. The only exception is in plant production where changes in growing season length and adapted crop choices are perceived beneficial. Addressing such adaptation opportunities, which are indicated by integrated modelling studies at least for one case study region (Schönhart et al., 2016) should thus be part of the research agenda, the policy making process and awareness-raising campaigns targeting farmers.

5.3. Effects: effects of private climate change adaptation

Private adaptation is intended to produce on-farm benefits but may also result in positive and negative on-farm and off-farm effects. A broad variety of combined bio-physical and socio-economic effects are perceived by the agricultural experts including synergies and trade-offs for the environment, climate change mitigation, agricultural production and income, human and social resources, and other economic sectors. This finding is also supported by quantitative assessments on climate change in the region and beyond. For instance, Kirchner et al. (2015) and Schönhart et al. (2016) show that the economically rational choice of private

adaptation may lead to an increase or decrease in topsoil organic carbon and greenhouse gas emissions, depending on the climate change scenario. Fertilization levels are likely to change with altered vegetation periods and CO_2 fertilization (Kirchner et al., 2016). Fezzi et al. (2015) reveal a strong spatial heterogeneity of potential effects of private adaptation on future river water quality indicating that the direction of change is associated to bio-physical conditions. Monitoring and periodic evaluation of the changing environment and adaptation measures could inform future private and public adaptation in order to reduce potential maladaptation in agriculture.

5.4. Responses: relationships between private and public climate change adaptation

Perceived relationships between private and public climate change adaptation are relevant for strengthening the science-policy-society interface. In particular, agricultural experts expect public adaptation to facilitate private adaptation that is robust to a range of plausible futures, new to the resource system or region, leads to positive off-farm effects, has high investment costs or requires collaborative efforts to ensure long-term effectiveness. Robust adaptation, which is typically low-regret, has been suggested in order to deal with inherent uncertainties in future climate change (Adger et al., 2008). For instance, the development of drought resistant crops is classified as robust (Hallegatte, 2009) and public incentives are legitimate because plant breeding may reduce the expansion of global agricultural land and greenhouse gas emissions (Lotze-Campen et al., 2015). New adaptation includes both, existing adaptation that is transferred to a new region and truly novel approaches (Kates et al., 2012). Its implementation may be cost-intensive, risky and limited by inflexibilities in the legal environment, which calls for public efforts. Private adaptation that requires collaboration between actors with similar or diverging interests in order to ensure its long-term effectiveness may benefit from external facilitation or regulation. For instance, adaptation to a higher incidence of thermophilic pests such as the western corn rootworm may benefit from collective action (Ervin and Jussaume, 2014).

According to the results of the semi-structured interviews, public adaptation is suggested to focus on the provision of a supportive and flexible organizational environment, consistent and transparent legal and policy environments and easy access to educational, informational, technical and financial infrastructure. Some of these demands (e.g. transparency) are known from the principles of 'good governance' (see e.g. Lockwood, 2010) and may be complemented by findings from the 'adaptive governance' literature which investigates how uncertainties and abrupt changes can be managed by multi-level governance modes (see e.g. Novellie et al., 2016; Olsson et al., 2006). For instance, regional adaptation partnerships, which foster networking between private and public actors and mediate between governmental levels have been identified as a promising approach for facilitating climate change adaptation (Bauer and Steurer, 2014). Similarly, collaboration between policy makers, policy implementers and users has been recommended for developing policy guidelines and adaptation plans in order to ensure that spatio-temporal scales and financing mechanisms match the requirements for adaption (Novellie et al., 2016). Fröhlich and Knieling (2013) suggest that private and public actors should be involved in the development and design of formal (e.g. regulations), economic (e.g. taxes and subsidies), and informal instruments (e.g. information and education) to foster adaptation governance. The identified need for public adaptation to provide access to infrastructure corresponds to empirical findings from other case study regions (e.g. Deressa et al., 2009; Dowd et al., 2014; Kassie et al., 2013; Li et al., 2017).

6. Conclusions

We provide the novel *S*timuli-*A*ctions-*E*ffects-*R*esponses *(SAER)*-framework to investigate and analyze perceived relationships between private and public climate change adaptation. The *SAER*-framework captures systematically the perceived bandwidth of adaptation stimuli, private adaptation actions, adaptation effects and public responses. It has been developed and tested in an iterative process by combining deductive and inductive approaches, i.e. theoretical knowledge from the climate change adaptation literature has been combined with empirical findings from two case study regions. The case study regions are heterogeneous in pedoclimatic conditions, employed farming systems and regional vulnerabilities of the agricultural sector to climate change and thus provide useful insights for refining and testing the *SAER*-framework.

The *SAER*-framework has proven effective in understanding the process of private adaptation in order to identify opportunities to facilitate and coordinate private and public adaptation in the context of Austrian agriculture and forestry. Thus, it can serve as a novel framework for exploring the relationships between private and public adaptation at regional scale and for evaluating synergies and trade-offs between private and public adaptation actions.

However, the results of such analyses or evaluations may be driven by the categories currently considered in the *SAER*-framework. Hence, further empirical testing is needed to determine applicability and ease of adoption in other geographical regions with similar or contrasting production conditions and other socio-economic contexts where farmers employ different farming systems. The suggested modular structure of the *SAER*-framework may facilitate adjustments such that modules and their relationships can be re-combined, modified or amplified. We recommend reasonable modifications, extensions or specifications, if applied at farm level or in another region. For instance, the interviewed agricultural experts perceive forest production as an integral part in agricultural adaptation because many farmers manage both farmland and forests in the case study regions, which may be not relevant in other regions.

In the Austrian context, the findings from the semi-structured interviews represent diverse perceptions of regional agricultural experts, which directly feed into the *SAER*-framework. Additional or divergent perceptions may exist by other actors from the region or beyond (e.g. policy makers from different administrative levels) and in other agricultural production regions. They would need to be identified and considered when applying the *SAER*-framework in the respective context.

Related to the proposed *SAER*-framework, further research opportunities arise. For instance, a comparative analysis of multiple regional case studies could be conducted in order to evaluate which combinations of adaptation stimuli most likely lead to or limit private adaptation, which private adaptation actions are most often adopted in different regions, which intended and unintended effects of adaptation actions are most frequently reported, and which public interventions are rated most effective for increasing farmers' adaptation actions in similar contexts. Furthermore, we propose to analyze systematically how private and public actors can cooperate in developing, assessing, implementing, monitoring and evaluating adaptation actions in order to successfully reduce the currently perceived adaptation deficit in agriculture. In this respect, the *SAER*-framework could be extended by considering different types and levels of cooperation, which may include formal hierarchies and informal networks as well as multi-level partnerships and interactions.

Off-farm stimuli and effects could be further differentiated by spatial or administrative level (e.g. whether a stimulus appears at regional, national, supranational or global level) in order to identify at which level public actions could be most effective. Finally, the role of uncertainty and time may be of interest in the context of agricultural adaptation. Investigations could focus on how adaptation stimuli change over time and on how residual damages (i.e. impacts that remain even though adaptation takes place) are evaluated by private and public actors.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.12.063.

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